Section 2

Basic Physics of Radiofrequency

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2.1 Symbols and Units

E	Electric field, in units of Volts per meter (V/m)
H	Magnetic field strength in units of Ampere per meter (A/m)
B	Magnetic flux density in units of Tesla (SI) or Gauss (CGS)
f	Frequency of a wave, in units of Hertz (Hz)
λ	Wavelength of a wave, in meters (m)
A	Ampere, unit of electric current
V	Volt, unit of electric voltage
T	Tesla, SI unit of magnetic flux density
G	Gauss, CGS unit of magnetic flux density
W	Watt, unit for electric power
S	Power density, in units of Watts/m^2
m	Meter, unit for distance
dB	Decibel, logarithmic unit (dimensionless)
dBm	Decibel-milliWatt, logarithmic unit (dimensionless)
dBW	Decibel-Watt, logarithmic unit (dimensionless)
dBi	Gain of an antenna relative to an isotropic RF source (dimensionless)
Ω	Ohm, electrical unit of resistance

2.2 Useful Definitions

2.2.1 Electromagnetic (EM) radiation

EM radiation is the energy transmitted through space in wave form, which can be characterized in terms of a wavelength **λ** or a frequency **f**.

2.2.2 RF antenna

An antenna is a device used to emit and receive radiofrequency (RF) waves. As an emitter, it transforms high frequency signals traveling on a conductor into electromagnetic (EM) waves in free space.

2.2.3 Radiofrequency

Radiofrequency is a frequency within the electromagnetic spectrum used for radio transmission. For purposes of this toolkit, the frequency range of interest is 100 kHz to 300 GHz, as shown in Table 1.[1]

Table 1. Frequency band designations

FREQUENCY	BAND CODE	BAND DESCRIPTION
30 Hz-300 Hz	SLF	Super Low Frequency
300 Hz-3000 Hz	ULF	Ultra Low Frequency
3 kHz-30 kHz	VLF	Very Low Frequency
30 kHz-300 kHz	LF	Low Frequency
300 kHz-3 MHz	MF	Medium Frequency
3 MHz-30 MHz	HF	High Frequency
30 MHz-300 MHz	VHF	Very High Frequency
300 MHz-3 GHz	UHF	Ultra High Frequency
3 GHz-30 GHz	SHF	Super High Frequency
30 GHz-300 GHz	EHF	Extremely High Frequency

2.2.4 Wavelength of RF waves

Distance covered by one complete cycle of the RF wave, as shown in Figure 1.

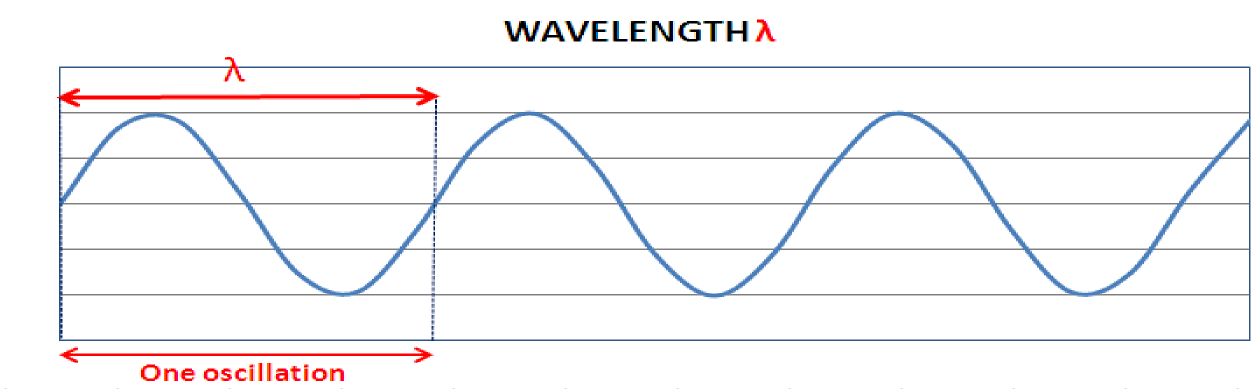


Figure 1. Wave Characteristics

2.2.5 Frequency of RF waves

Frequency of RF waves is the number of EM waves passing a given point in one second. The frequency is expressed in Hertz (Hz).

2.2.6 Bandwidth of an RF antenna

The bandwidth of an antenna refers to the range of frequencies over which the antenna operates correctly.

2.2.7 Power density

Power density is the power per unit area perpendicular to the direction of propagation, usually expressed in terms of Watts per square meter (W/m^2) or milliWatts per centimeter-squared (mW/cm^2).

2.2.8 Decibel (dB)

A decibel is a measure of the increase or decrease in power, P, at two points 1 and 2 expressed in logarithmic form:

$$\text{Power Ratio in dB} = 10\text{Log}\left(\frac{P_1}{P_2}\right) \qquad \textbf{(2.1)}$$

- *Decibel-milliwatt (dBm)*:

Electrical power unit in decibels referenced to 1milliWatt (mW), as expressed below:

$$P(\text{dBm}) = 10\text{Log}[\frac{P(\text{mW})}{1\text{ mW}}] \qquad \textbf{(2.2)}$$

- *Decibel-Watt (dBW)*:

Electrical power unit in decibels referenced to 1Watt (W), as expressed below:

$$P(\text{dBW}) = 10\text{Log}[\frac{P(\text{W})}{1\text{ W}}] \qquad \textbf{(2.3)}$$

2.2.9 Antenna gain/loss in dBi

This is the antenna's gain or loss G over a theoretical **isotropic** antenna (radiating evenly in all directions).

$$Gain\ G\ (dB) = 10Log(\frac{P_1}{P_2}) \qquad (2.4)$$

Where:

- $\mathbf{P_1}$ is the power from the antenna at a point X in space.
- $\mathbf{P_2}$ is the power from a hypothetical isotropic radiator at the same point X.

Example:

If an antenna has a gain G of 6 dBi in a certain direction, it means that the power of the transmitter is multiplied by 4, as shown below:

$$\frac{P_1}{P_2} = Inv\ [Log_{10}\left(\frac{6}{10}\right)] = 10^{0.6} = 4 \qquad \textbf{(2.5)}$$

2.2.10 Equivalent isotropically radiated power (EIRP)

The equivalent isotropic radiated power (EIRP) is defined as the product of the power supplied to the antenna $\mathbf{P_t}$ and the antenna gain $\mathbf{G_t}$, both quantities expressed in linear terms (not in decibels):

$$\mathbf{EIRP\ (W) = P_t\ (W)\,.\,G_t} \qquad \textbf{(2.6)}$$

It is the power that would be radiated by an isotropic source if it had an input power equal to $\mathbf{P_t}\ \mathbf{G_t}$.

In equation *(2.6)*, **EIRP** and $\mathbf{P_t}$ are expressed in units of Watt while $\mathbf{G_t}$ is dimensionless.

In decibels (dimensionless), EIRP is equal to the sum of $\mathbf{P_t}$ (dBW) and $\mathbf{G_t}$ (dBi):

$$\mathbf{EIRP(dBW) = P_t(dBW) + G_t(dBi)} \qquad (2.7)$$

Example:

Suppose $\mathbf{P_t}$ = 20 Watt and the antenna Gain $\mathbf{G_t}$=5

- In units of Watt, EIRP is equal to: **20 W x 5 = 100 W**
- In units of decibel-power (dimensionless):

  $\mathbf{P_t}$ (dBw) = 10 Log (20) = 13.01

  $\mathbf{G_t}$ (dBi) = 10 Log (5) = 6.99

Therefore: $\mathbf{EIRP}\ (\mathbf{dBW}) = \mathbf{10\ Log}\ (\mathbf{20}) + \mathbf{10\ Log}\ (\mathbf{5}) = \mathbf{13.01} + \mathbf{6.99} = \mathbf{20}$ dBw *(2.8)*

Note: In equations *(2.6)* and *(2.7)*, signal losses in cables are assumed negligible.

2.2.11 Continuous RF wave (CW)

A continuous radiofrequency wave is a RF signal that is not altered by modulation. It is therefore is described by a constant frequency, constant amplitude, and steadily advancing phase. In other words, continuous waves are successive oscillations which are identical under steady-state conditions.

2.2.12 Modulation of RF waves

Wave modulation occurs when some characteristic of the wave is varied.

a. Pulse modulation:

In pulse modulation, pulsed waves are emitted in short pulses, i.e., RF energy is rapidly switched ON and OFF, as shown in Figure 2.

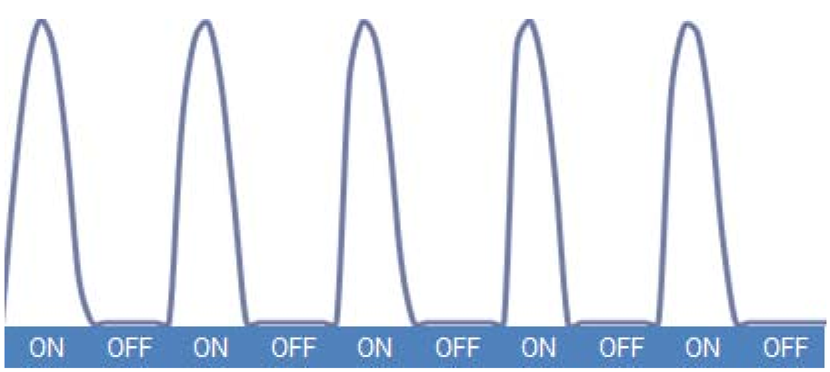


Figure 2. Pulsed waves

For example, Global System for Mobile Communications (GSM) technology uses eight slots. The assignment of one slot per user gives rise to the pulsed nature of the wave; a GSM phone will only be transmitting 1/8th of the time, i.e., 1/8th duty cycle.[2]

Other examples: keyless entry, pulsed NMR systems, analog or digital radar for airports, ships, speed detection, military, satellites, electronic test equipment.

b. Amplitude modulation:

RF waves are continuously emitted with changing energy (amplitude), as shown in Figure 3.

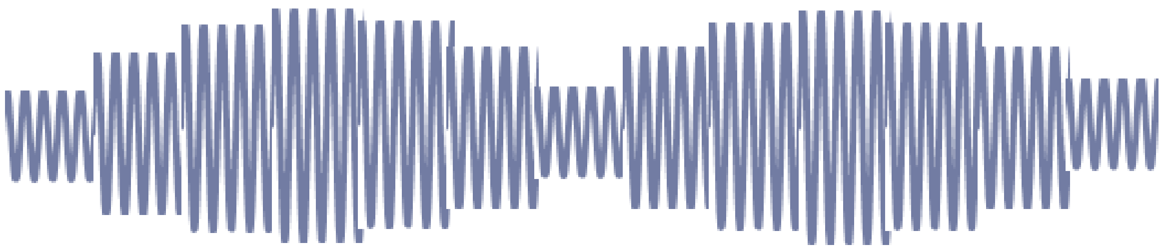


Figure 3. Amplitude-modulated waves

Examples of amplitude modulation: AM radio, amateur radio.

c. Frequency modulation:

RF waves have constant amplitude with change of frequency in small amounts, as shown in Figure 4.

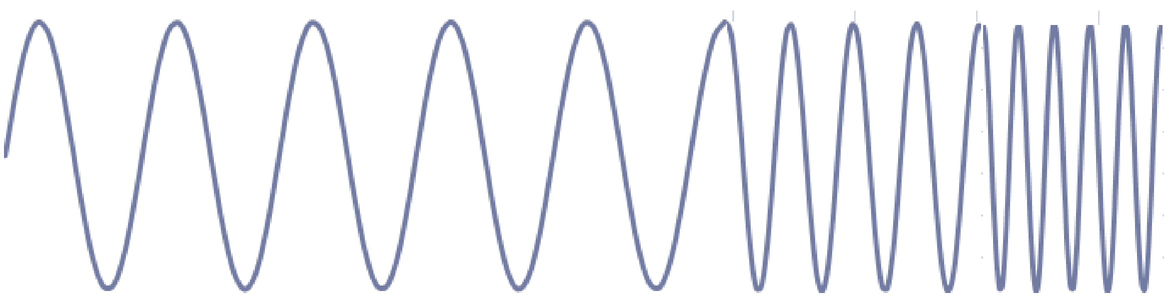


Figure 4. Frequency-modulated waves

Examples of frequency modulation: FM radio, amateur radio, data and fax modems, telemetry, radar, seismic prospecting and newborn EEG seizure monitoring[3]:

2.2.13 Electric field

The region surrounding an electric charge, in which the magnitude and direction of the force on a hypothetical test charge is defined at any point. The electric field produces a force on electrically charged objects.

Electric field strength E:

The magnitude of the electric field vector (in units of Volts/meter, V/m)

Magnetic field:

A force field associated with changing electric fields (when electric charges are in motion). Magnetic fields exert deflective forces on moving electric charges.

A magnetic field can be specified in two ways: as magnetic flux density B or magnetic field strength H.

Magnetic flux density B:

B is the amount of magnetic flux through a unit area taken perpendicular to the direction of the magnetic flux, in SI units of Tesla (T) or CGS units of Gauss (G).

$$1 \text{ Gauss} = 10^{-4}\text{Tesla} = 100\mu\text{Tesla} \quad (2.9)$$

Magnetic field strength H:

H is the magnitude of the magnetic field vector (in units of Amperes/meter, **A/m**)

Relation between B and H:

The two quantities are related by the expression:

$$B = \mu H \quad (2.10)$$

Where μ is the magnetic permeability. In a vacuum and in air, as well as in non-magnetic (including biological) materials, μ has the value $4\pi\ 10^{-7}$ expressed in units of Henry per meter ($H.m^{-1}$). Therefore, a magnetic field can be described by either of the two quantities, B or H.

2.2.14 Power density in the far field

The power density S is the product of the electric field E and the magnetic field H:

$$S = E.H \quad (2.11)$$

In the far field, an estimate of the RF power density can be determined by means of the following equation[1]:

$$S = \frac{P_t\, G_{max} \delta\, \gamma}{4\pi R^2} \quad (2.12)$$

Where:

- S is the power density (Watt/m^2)
- P_t is the power of the transmitter (Watt)
- G_{max} the maximum Gain of the antenna (dimensionless)

- δ the duty cycle of the RF source (dimensionless)
- γ a factor that accounts for possible ground reflections (dimensionless)
- R the distance from the RF source (meters)

2.2.15 Root- mean- square (rms) Electric (E) and magnetic (H) fields

This is the square root of the average of the squares of the instantaneous **E field** or **H field** taken over a time interval.

For example, if n values E1, E2, … En of the electric field are recorded during an interval of time, the rms electric field current is calculated as follows:

$$rms\ E = \sqrt{\frac{1}{n}(E_1^2 + E_2^2 + E_3^2 + \cdots E_n^2)} \qquad \textbf{(2.13)}$$

Similarly, the rms magnetic field is:

$$rms\ H = \sqrt{\frac{1}{n}(H_1^2 + H_2^2 + H_3^2 + \cdots H_n^2)} \qquad \textbf{(2.14)}$$

2.3 General Properties of RF Waves[4]

RF waves are EM waves that:

- can be found in nature or be man-made
- propagate in free air and dense media. Their propagation obeys the inverse square law at sufficient distance from the antenna (far field).
- travel at the speed of light (300,000 Km/second)
- carry energy as they propagate
- can transfer their energy to matter
- can be used to carry information
- can be broadcast outwards to reach many locations or can be formed into beams to reach a particular spot
- can be reflected or refracted when interacting with a dense medium
- can travel great distances
- travel in straight lines
- can pass through walls
- can be captured by placing a metal rod, a loop, parabolic metal dish, or horn in its path.

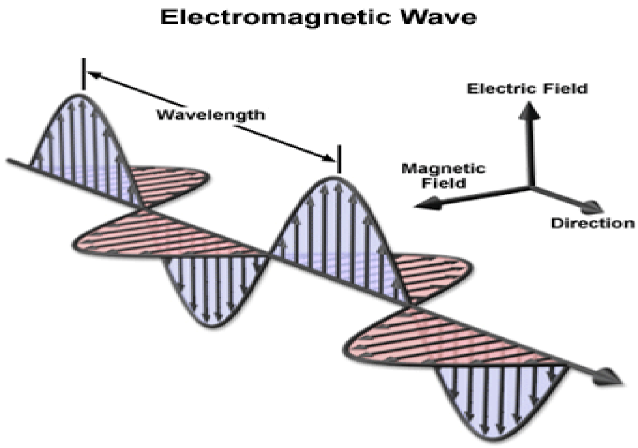
2.4 RF Fields

The electromagnetic field is composed of an electric field E and a magnetic field H. They both produce forces on electric charges.

Static electrical charges produce an electric field while charges in motion produce a magnetic field.

A changing magnetic field can move electric charges to induce currents in its interaction with a medium.

An RF wave is a moving electromagnetic field that has velocity in the direction of travel and components of electric field E and magnetic field H arranged at right angles to each other (Figure 5). The RF field transmits and receives RF energy through free space.

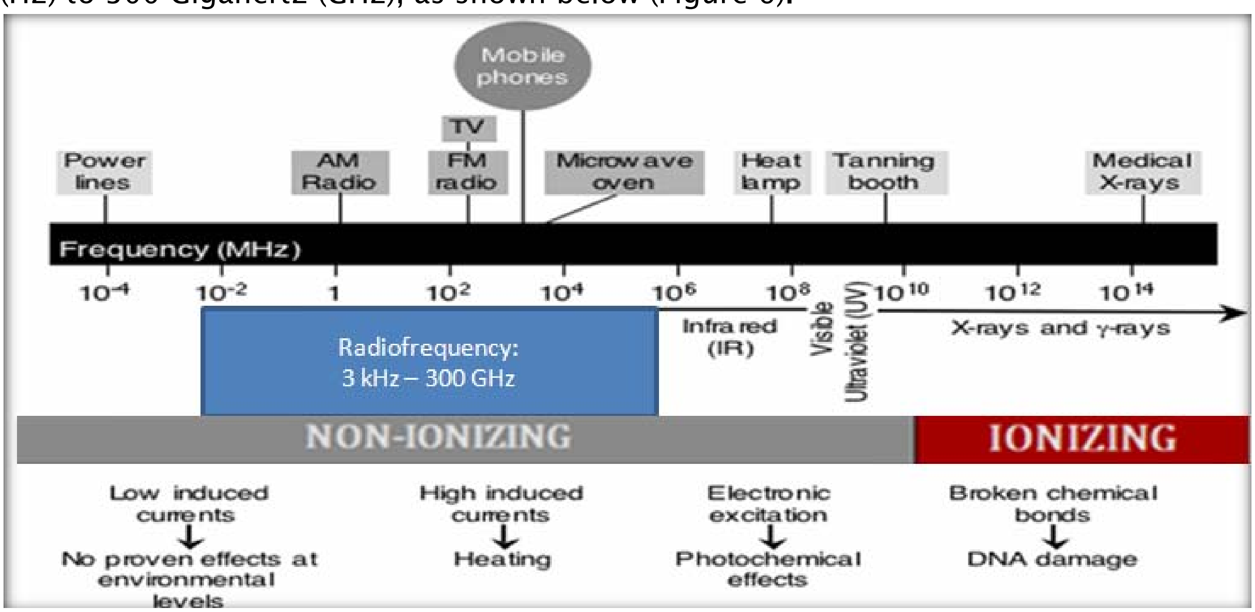


"Electromagnetic wave", used for educational and research purposes, courtesy of Magnet Lab, Florida State University

Figure 5. Schematic representation of the propagation of RF waves

2.5 RF Waves in the Electromagnetic Spectrum

RF waves are part of the electromagnetic spectrum in the frequency range of 300 Hertz (Hz) to 300 Gigahertz (GHz), as shown below (Figure 6).



Adapted from: Foster and Moulder (2000).[5]

Figure 6. Non-ionizing fields spectrum

2.6 Characteristics of RF Fields

EM waves have a wavelength and a frequency related by:

$$\lambda = \frac{c}{f} \quad \text{2.15)}$$

Where:

- c is the velocity of light = 3 10^{8} m/s= 300,000 Kilometers per second (km/s)
- f is the frequency in Hertz (or sec^{-1})
- λ is the wavelength in meters (m)

RF waves can propagate through various media, particularly air. Their propagation characteristics depend on their frequency f (or wavelength λ) but also on the physical properties of the absorbing media. The speed of an RF wave in a vacuum is equal to the speed of light.

RF emitters transmit their signals in either Continuous Wave (CW) mode or Pulsed Wave (PW) mode.

In a CW mode, the waves are emitted in a continuous command. The power output of a continuous system is expressed in terms of average power.

In a PW mode, the waves are emitted in short pulses repeated at regular intervals. The output of a pulsed system is expressed in terms of peak power. The average power for a pulsed system is:

$$P_{avg} = D_c P_{max} \quad \text{(2.16)}$$

Where:

- P_{avg} is the average power in Watts (W)
- D_c is the duty cycle (dimensionless)
- P_{max} is the peak power in Watts (W)

2.7 Production of RF: RF Antennas

RF fields are produced by RF antennas. The role an RF antenna is to focus and intensify the initially generated waves. Two types of antennas are usually used for the production of RF: stationary antennas and rotating antennas.

2.7.1 Stationary antennas

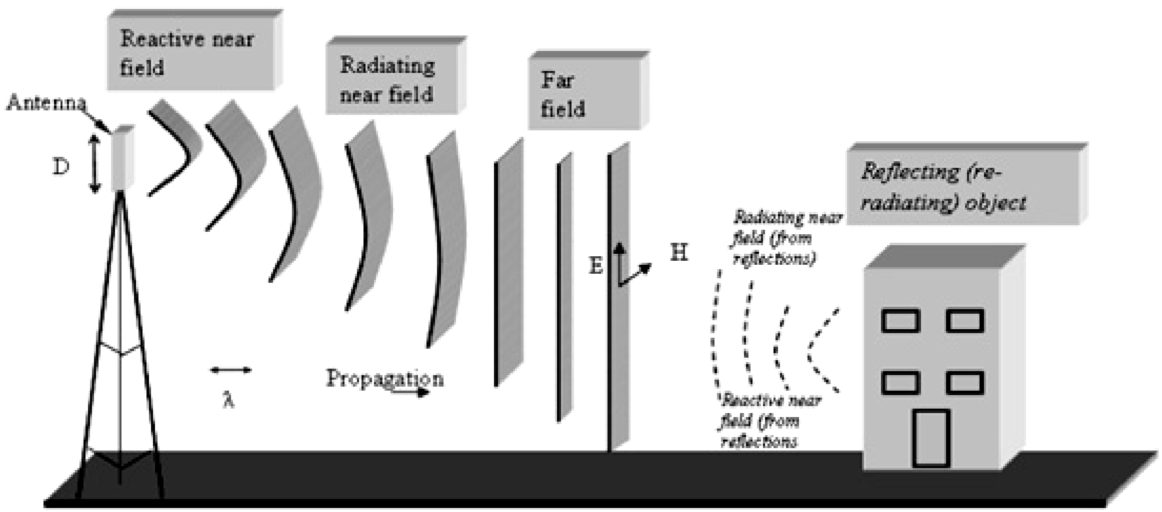
Stationary antennas are fixed antennas. They are widely used for radio broadcasting, mobile phones and base stations, FM radios, Wifi systems, cordless phones, GPS, etc. The size of the antenna is much larger than the wavelength λ of the emitted waves.

The antenna focuses the original RF signal into narrow and intense RF beams. The focusing potential of the antenna is quantified by its Gain G which is a measure of the proportion of the input power that is concentrated in a particular direction.

The RF waves generated by an antenna have different properties at varying distances from the RF source.

Three regions are commonly considered in the path of RF fields (Figure 7):

- The Near Field (nf)
- The Intermediate Field (if) also known as the Fresnel region
- The Far Field (ff) also known as the Fraunhofer region



"Near, Intermediate, and Far Fields", used for educational and research purposes, courtesy of International Commission on Non-Ionizing Radiation Protection (2009).[7]

Figure 7. Propagation of RF waves

2.7.1.1 The near field

The near field is the EMF that exists at the RF source and extends to a distance of one wavelength from the antenna.

In this region where the phase differences between waves emitted at different points of the antenna are relatively large, the relationship between the Electric Field E and the Magnetic Field H is not well defined.

The near field is divided into two sub-regions:

- The <u>reactive near field</u> where the strength decreases rapidly with distance from the antenna
- The <u>radiating near field</u> where the average power density remains fairly constant at different distances from the antenna, with some localized fluctuations.

The ideal radiating near field conditions occur at a distance D_{nf} from the antenna on the order of:

$$D_{nf} = \frac{\lambda}{2\pi} \quad \textit{(2.17)}$$

Where λ is the wavelength of the RF wave.

For example if the frequency of the RF wave is 900 MHz (i.e., λ=33 cm), the distance D_{nf} is about 5 cm.

It is assumed that the near field extends to a distance of the order of one wavelength λ. In the case of a 900 MHz wave, the near field would extend to a maximum distance of 33 cm from the antenna.

For large antennas with a dimension D (diameter or largest dimension of the antenna) larger than one wavelength, the radiating near field region extends from:

$$\frac{\lambda}{2\pi} \ to\ 0.5\frac{D^2}{\lambda} \quad \textit{(2.18)}$$

Regarding the power density of the RF waves in the near field and because of the phase differences, it is practical to consider that the peak power density all the way through the near field is four times the average power density of the antenna S_0, as follows:

$$S_{nf} = 4S_{0=}\frac{4P}{A} \quad \textit{(2.19)}$$

Where:

- P is the power output of the antenna (Watt)
- A is the area of the antenna (m^2)

In the near field region, it is useful to measure the electric field E (in Volts per meter) and the magnetic field H (in Amperes per meter) and compare the values to the Limits of Canada Safety Code 6.

The quantities E and H are related as follows:

$$Z = \frac{E}{H} \quad \textit{(2.20)}$$

Where Z is the impedance in air, in units of Ohms (Ω).

The value of the impedance Z is not constant in the near field. It could be lower than 377 Ohms if the predominant field is magnetic and larger than 377 Ohms if the predominant field is electric.

2.7.1.2 The intermediate field

It starts after the near field and ends before the start of the far field. In this region, because of the phase differences between waves, the RF power density alternates between maximum and minimum levels in a similar way to the near field. Therefore, the power density in the intermediate field also follows Equation ***(2.20)***.

The intermediate field extends from 0.5 D^2/λ to $2D^2/\lambda$ where D is the largest linear aperture dimension of the antenna and λ the wavelength of the wave.

2.7.1.3 The far field

The far field is the electromagnetic field located beyond the near field. It starts at a distance D_{ff} from the antenna defined as follows:

$$D_{ff} = \frac{2D^2}{\lambda} \tag{2.21}$$

(Note that in Canada Safety Code 6 it is recommended taking D_{ff} as $0.5D^2/\lambda$ meaning that the intermediate field could be considered part of the far field).

In the far field, the electric field E and the magnetic field H are orthogonal and the free space impedance is equal to **377 Ω**. Therefore, the relation between E and H in the far field is:

$$Z_0 = \frac{E}{H} = 377 \tag{2.22}$$

Consequently, the power density in the far field is equal to:

$$S = E.H = \frac{E^2}{377} = 377H^2 \tag{2.23}$$

In the far field, the measurement of only one quantity, E or H or S, is enough. The other quantities can be calculated by means of equation ***(2.23)***.

2.7.2 Rotating antennas

Rotating antennas transmit RF waves in a given direction part of the time. This type of antennas is usually used for search and detection purposes, e.g., radars.

2.8 References

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